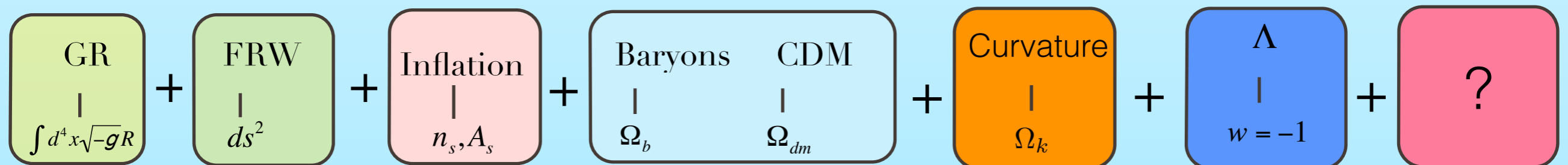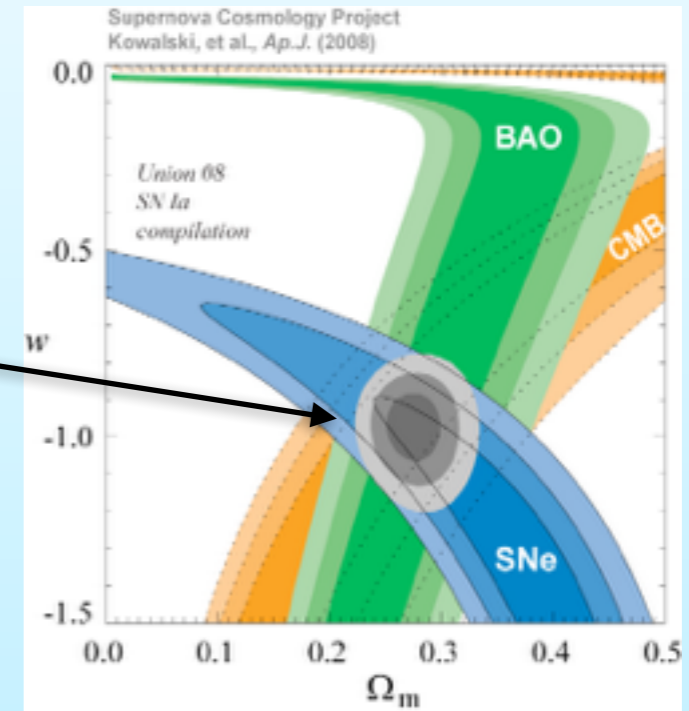# Update

## Jose A. Vazquez

BNL Meeting
November,

**Early Dark Energy**

# DR12

Cosmological parameter constraints from galaxy-galaxy lensing and galaxy clustering

BNL Meeting

November,

# The standard cosmological model



GR $+$ FRW $+$ Inflation $+$ Baryons CDM $+$ Curvature $+$ $\Lambda$ $+$ ?

$\int d^4x\sqrt{-g}R$ | $ds^2$ | $n_s, A_s$ | $\Omega_b$  $\Omega_{dm}$ | $\Omega_k$ | $w = -1$ |
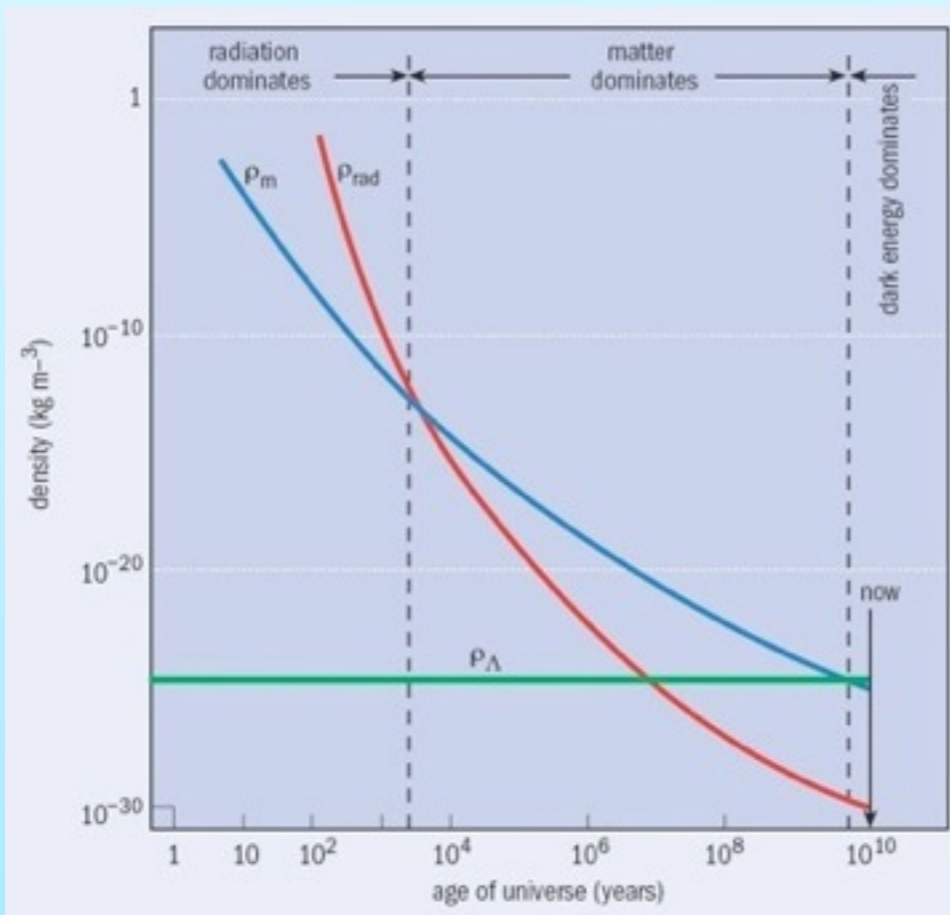
# Cosmological constant

cosmology vs particle physics:

$$\langle \rho \rangle \approx 2^{-10} \pi^{-4} G^{-2} = 2 \times 10^{71} \text{ GeV}^4 .$$

$$|\rho_V| \lesssim 10^{-29} \text{ g/cm}^3 \approx 10^{-47} \text{ GeV}^4 .$$

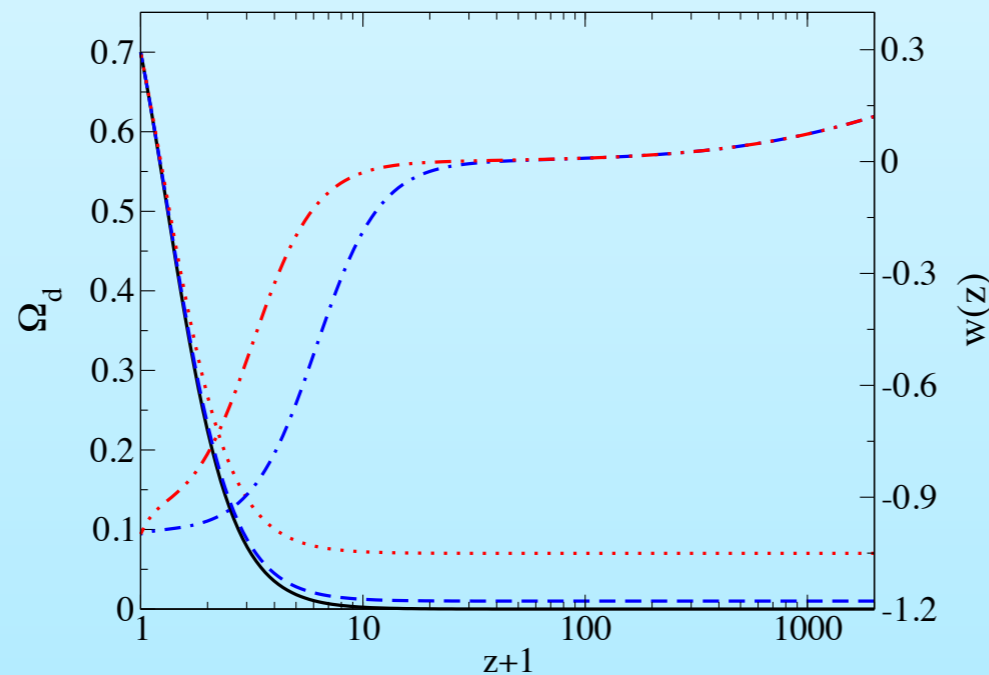clearly a discrepancy!!



fine tuning problem

coincidence problem

# Early Dark Energy

In typical dark energy models, DE is dynamically negligible at high redshifts.

Some scalar field potentials track the energy density of the dominant species during the radiation and matter dominated eras.

$$\Omega_{\mathrm{de}}(a) = \frac{\Omega_{\mathrm{de}} - \Omega_{\mathrm{de}}^e \left(1 - a^{-3w_0}\right)}{\Omega_{\mathrm{de}} + \Omega_m a^{3w_0}} + \Omega_{\mathrm{de}}^e \left(1 - a^{-3w_0}\right)$$



$$\Omega_{\mathrm{de}}^e$$

- To describe the BAO peak;

Across the line of sight

$$D_C(z) = \frac{c}{H_0} \int_0^z dz' \frac{H_0}{H(z')}$$

Along the line of sight

$$D_H(z) = c/H(z)$$

$$D_M(z)/r_d = \alpha_\perp D_{M,\mathrm{fid}}(z)/r_{d,\mathrm{fid}}$$

$$D_H(z)/r_d = \alpha_\parallel D_{H,\mathrm{fid}}(z)/r_{d,\mathrm{fid}}$$

The length of the ruler:

$$r_d = \int_{z_d}^\infty \frac{c_s(z)}{H(z)} dz$$



**The BAO signal**

# Some approximations

$$\rho_m(\hat{z}) + \rho_{\rm de}(z) = 3H^2(z)/8\pi G$$

$$H(z) = \left(100\,{\rm km\,s^{-1}\,Mpc^{-1}}\right) \times \left[(\Omega_m h^2)\,(1+z)^3\right]^{1/2}$$
$$\times \left[1 + \rho_{\rm de}(z)/\rho_m(z)\right]^{1/2} \ .$$

$$\Omega^e_{\rm de}/\Omega_m(z) \approx \Omega^e_{\rm de}/(1-\Omega^e_{\rm de})$$

## at high redshift

• $H(z)$

is higher in the early dark energy model by a factor $(1 - \Omega^e_{\rm de})^{-1/2}$, and $D_H(z)$ is smaller by the same factor.

• the boosted energy density in this era reduces $r_d$ sound horizon by a factor $(1 - \Omega^e_{\rm de})^{1/2}$

• $D_H(z)$ is smaller by the same factor

$$\alpha_\parallel$$

## at low redshift

$$D_M(z) = \frac{c}{H_0} \int_0^z \frac{H_0}{H(z')} dz'$$

depends mainly on $H_0$

Therefore, to keep the value of $D_M(1090)/r_d$ fixed to the CMB constraint, one must increase $H_0$ by approximately $(1 - \Omega^e_{\rm de})^{-1/2}$
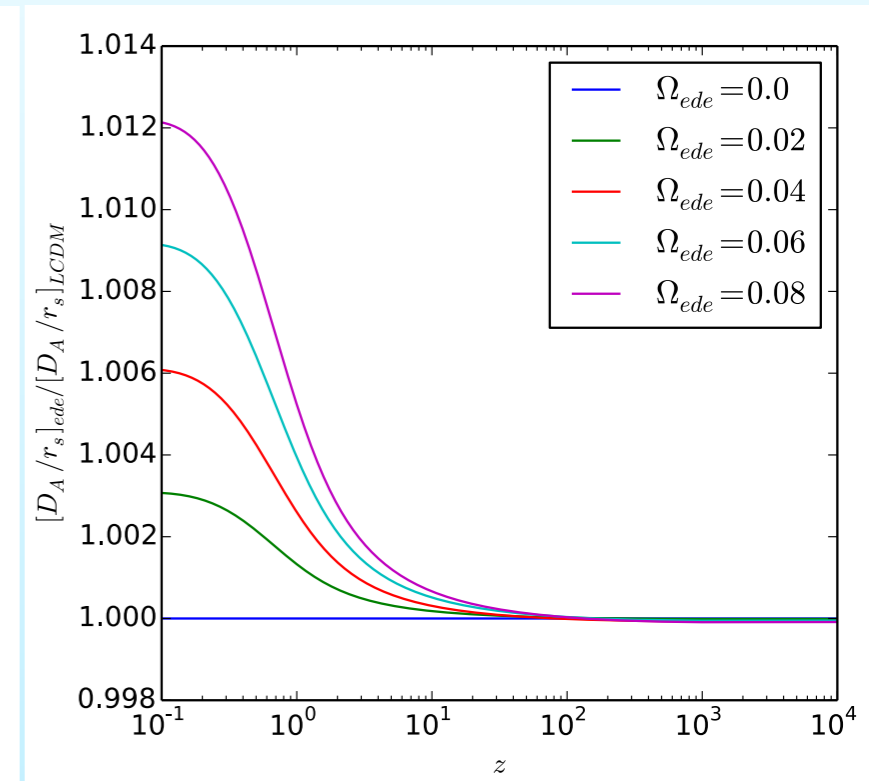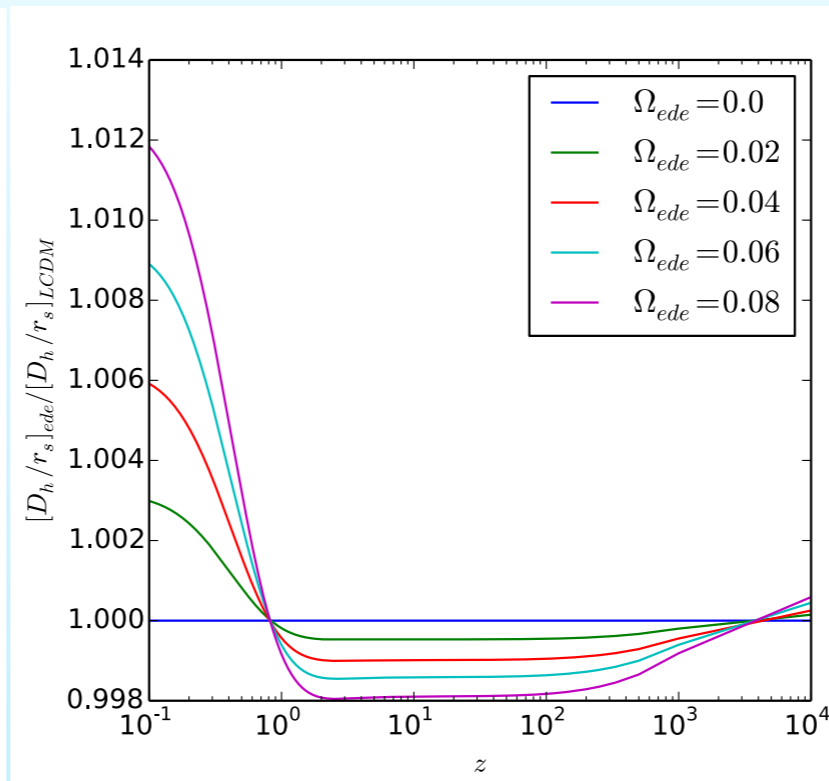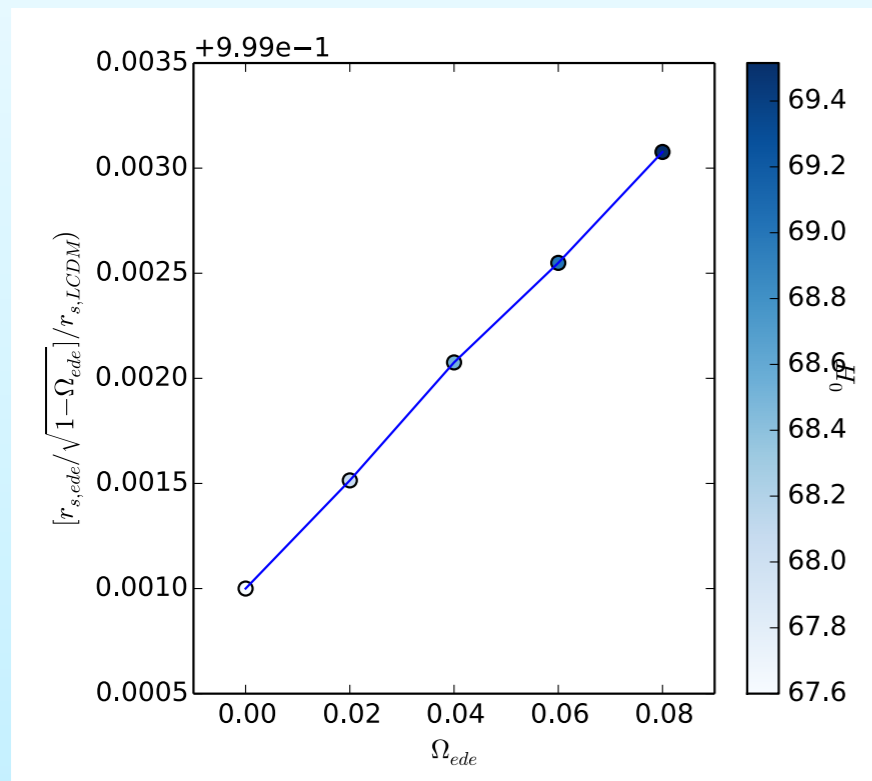
$$\alpha_\perp$$

# Early Dark Energy

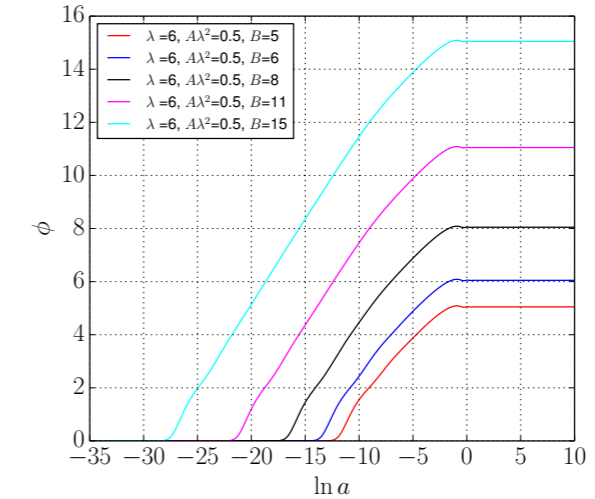$r_d$
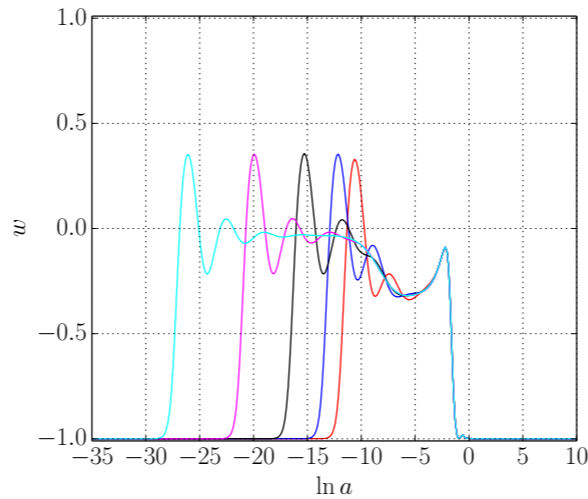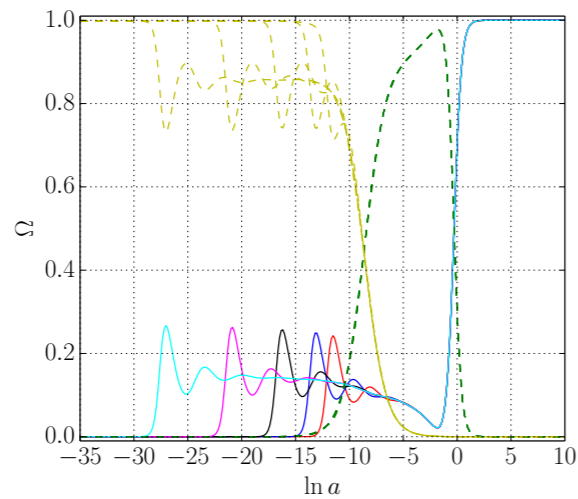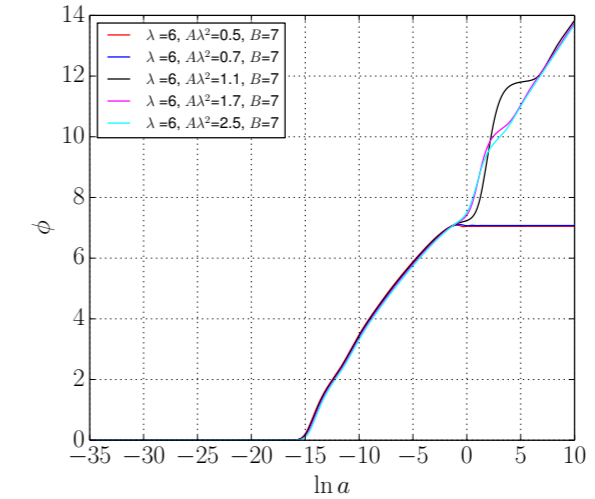
sound horizon by a factor $(1 - \Omega_{de}^e)^{1/2}$

$$\alpha_\parallel = \frac{r_d / [r_d]_{fid}}{D_M / [D_M / r_d]_{fid}}$$

$D_M / [D_M / r_d]_{fid}$

$\alpha_\perp$

PlanckWP
$\Omega_{de}^e = 0.02$
$\Omega_{de}^e = 0.04$
$\Omega_{de}^e = 0.08$
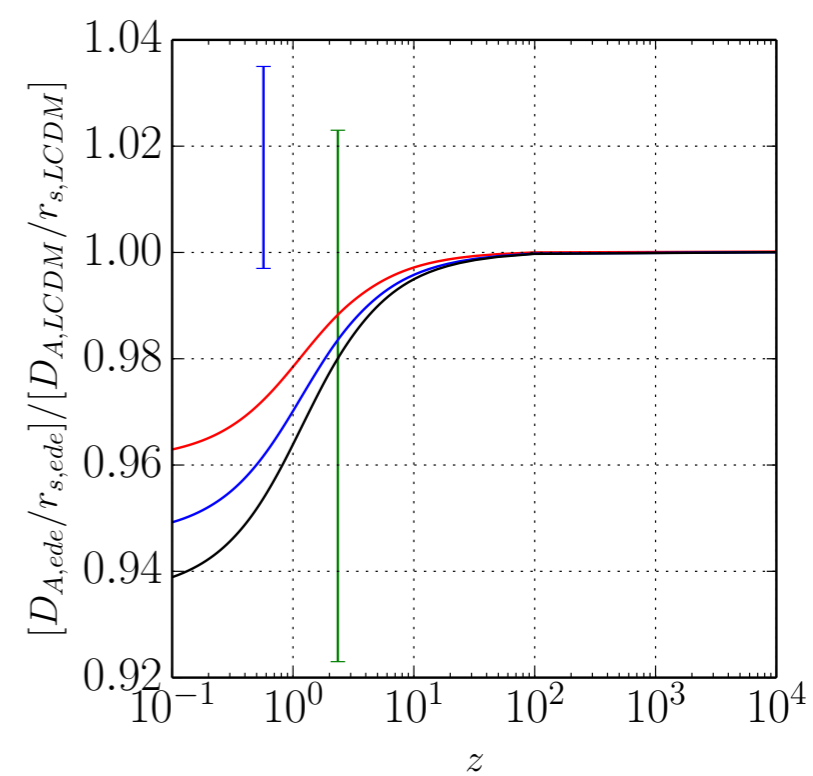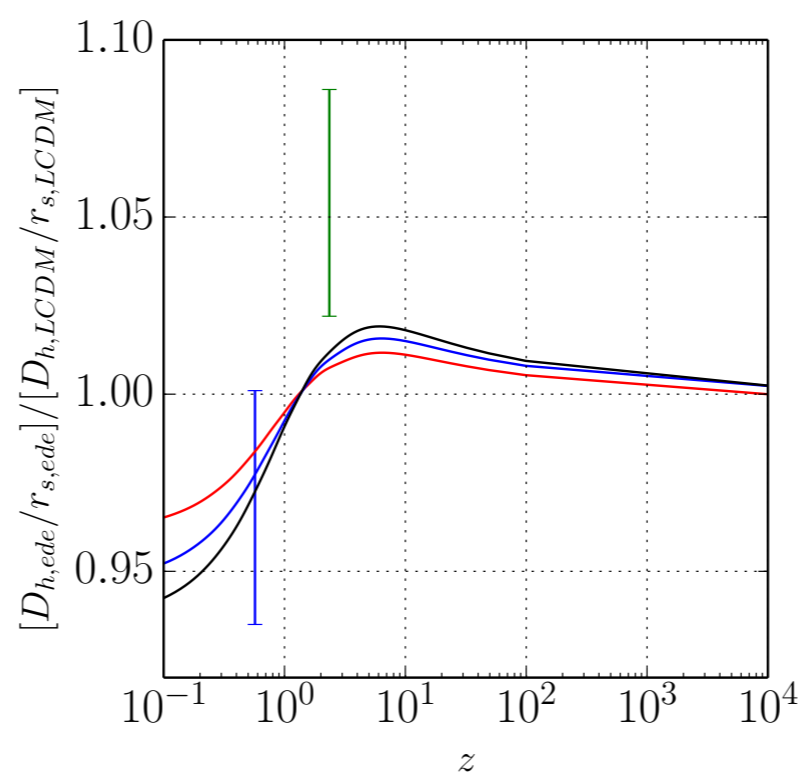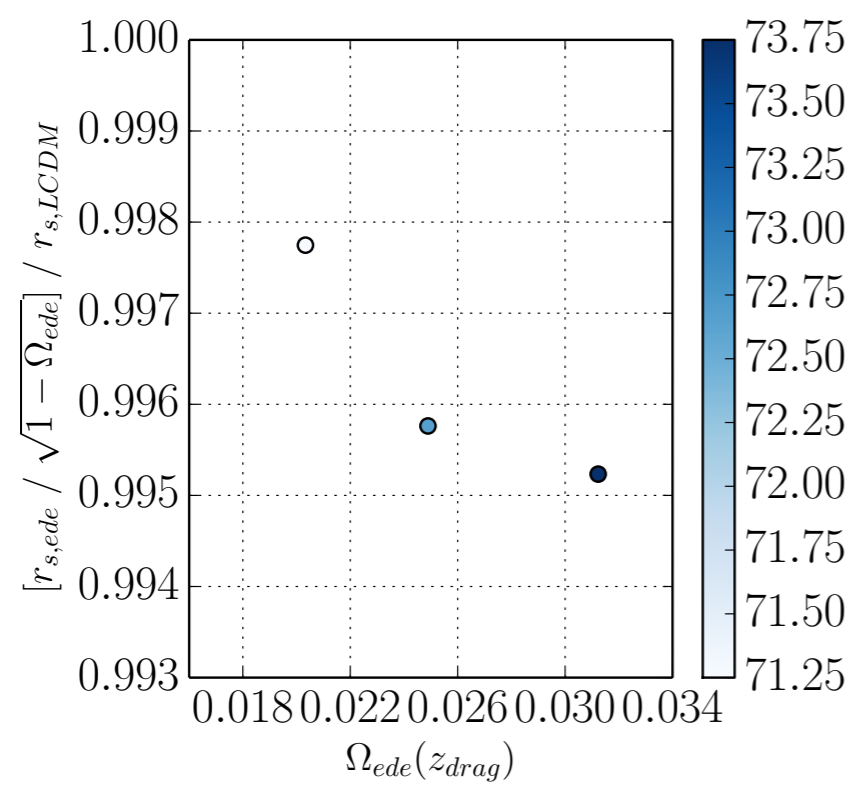
# Scalar Field cosmology
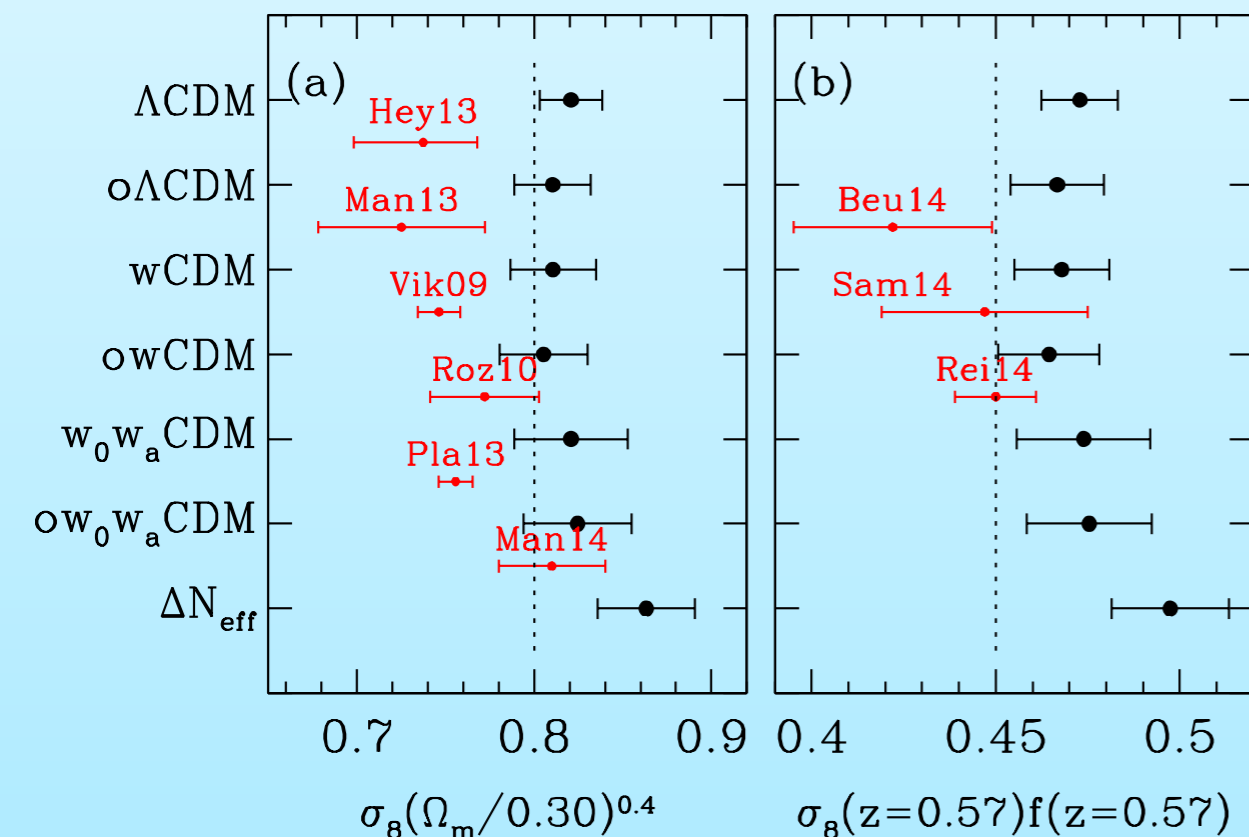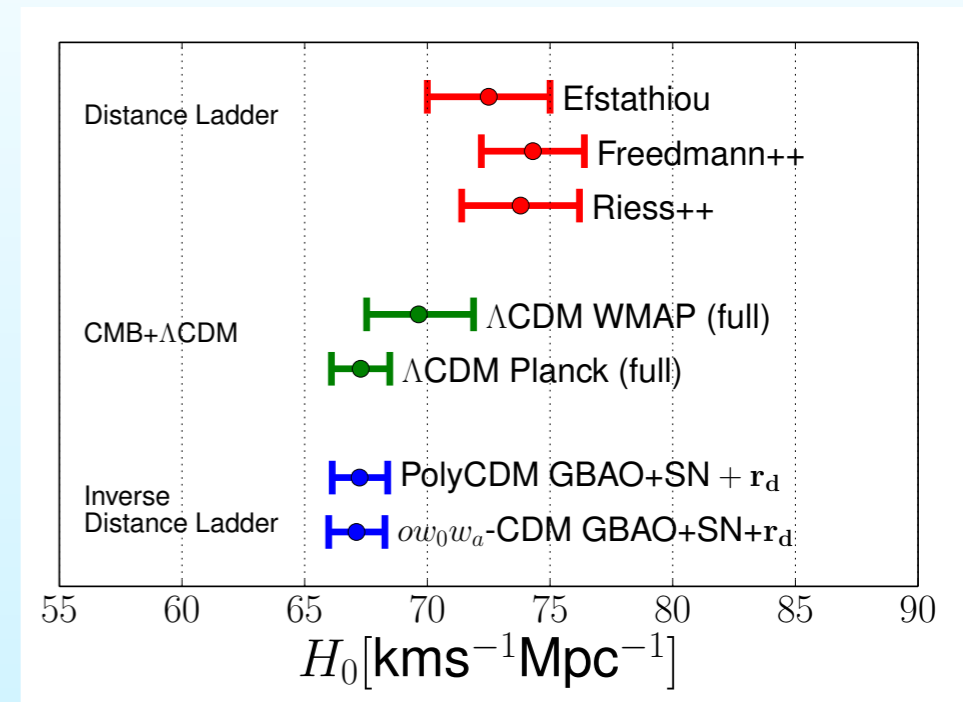
$$V(\phi) = V_0[(\phi - B)^2 + A]\exp(-\lambda\phi)$$
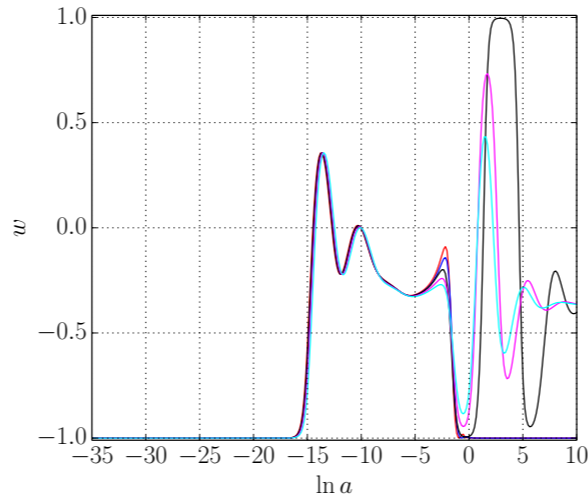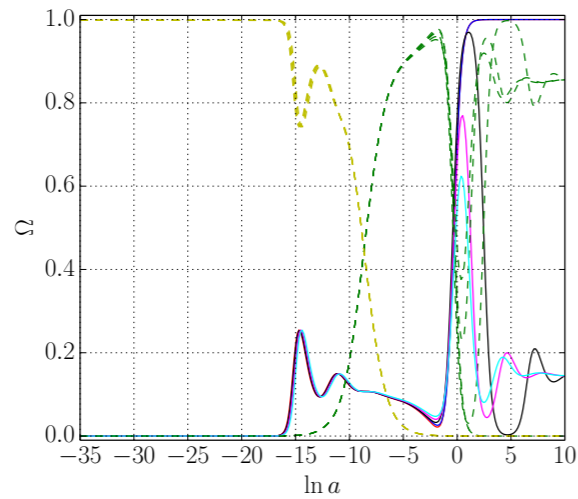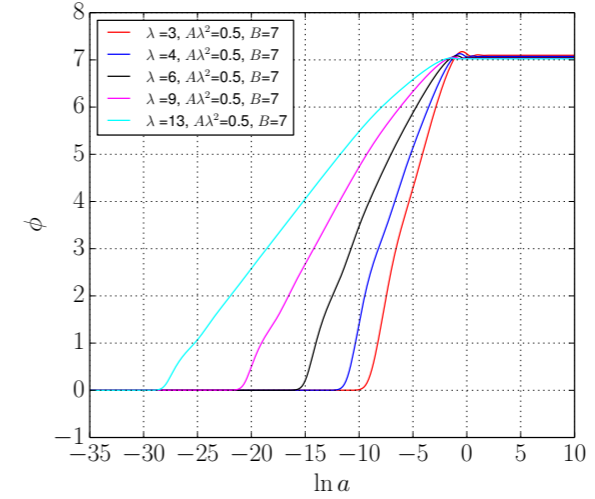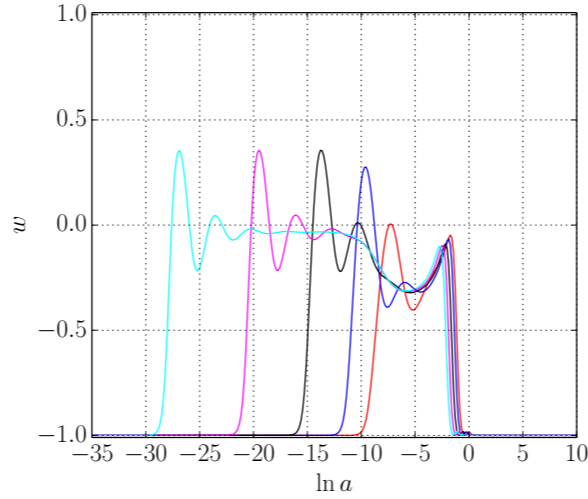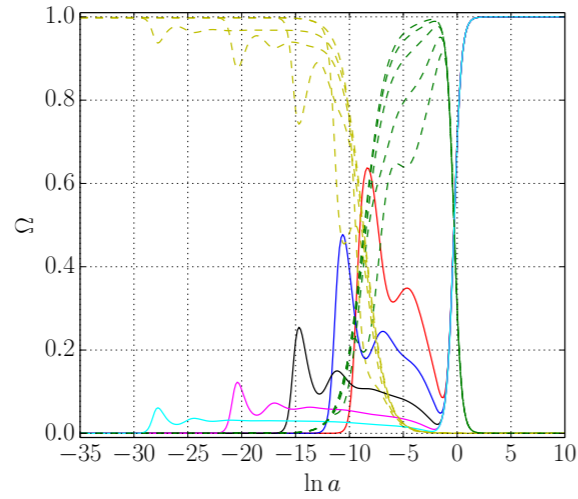
# Scalar Field cosmology

# Scalar Field Cosmology



Intriguingly, non-zero $\Omega_e$ with rescaled $r_d$ reduces tension with distance-ladder measurements of $H_0$ and with the level of matter clustering from cluster masses, weak lensing, and redshift-space distortions.

Increasing the early dark energy fraction reduces the value of $\Omega_m$ (see Fig. 13) and will also suppress growth of structure relative to $\Lambda$CDM.

Plots/labels visible:

- $w_a$CDM — Pla13
- $w_a$CDM — Man14
- $\Delta N_{eff}$
- $\sigma_8(\Omega_m/0.30)^{0.4}$
- $\sigma_8(z=0.57)f(z=0.57)$
- $\sigma_8(z=2.5)$

Right panel (H0 figure):

Distance Ladder: Efstathiou, Freedmann++, Riess++

CMB+$\Lambda$CDM: $\Lambda$CDM WMAP (full), $\Lambda$CDM Planck (full)

Inverse Distance Ladder: PolyCDM GBAO+SN + $r_d$, $ow_0w_a$-CDM GBAO+SN+$r_d$

$H_0[\text{kms}^{-1}\text{Mpc}^{-1}]$ axis: 55, 60, 65, 70, 75, 80, 85, 90

Bottom left panel:

(a) and (b)

Rows: $\Lambda$CDM, $o\Lambda$CDM, wCDM, owCDM, $w_0w_a$CDM, $ow_0w_a$CDM, $\Delta N_{eff}$

Labels: Hey13, Man13, Vik09, Roz10, Pla13, Man14, Beu14, Sam14, Rei14

Axis (a): 0.7, 0.8, 0.9 — $\sigma_8(\Omega_m/0.30)^{0.4}$

Axis (b): 0.4, 0.45, 0.5 — $\sigma_8(z=0.57)f(z=0.57)$